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Review

Assessment of Effects on Non-target Plants from Sulfonylurea Herbicides Using Field Approaches

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Abstract: Since their introduction in the early 1980s, there have been a number of field studies conducted to assess the effects of sulfonylurea herbicides on non-target plants (i.e. plants not labeled for use). In these studies a wide variety of plant response assessment techniques have been used to measure effects on non-target plants. This paper examines the relationship of short-term plant response measurements to plant productivity measurements such as yield or quality. Whether short-term plant response measurements have a practical degree of accuracy and precision appropriate for hazard assessment on non-target plants from sulfonylureas is discussed. A comprehensive review of published literature and unpublished field studies of the effects of sulfonylureas on the yield and quality of non-target plant species is reported. When this information is coupled with exposure factors and environmental fate characteristics, the risks to non-target plants from sulfonylureas are similar to those from other herbicides used at higher application rates. © 1998 SCI.

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1 INTRODUCTION

Sulfonylurea herbicides were first commercialized in 1981 with the introduction of chlorsulfuron for use in cereal crops. Additional crop-selective sulfonylureas have been introduced for use in a broad range of crops, including corn, soybeans, rice, oilseed rape, sugarbeets, and potatoes. Sulfonylureas are also used for non-selective control of annual and perennial grasses and broadleaf weeds in non-crop and industrial areas. Sulfonylurea herbicides act by inhibiting the enzyme acetolactate synthase (ALS), also called acetohydroxyacid synthase (AHAS), which participates in the biosynthesis of the branched-chain amino acids valine, leucine and isoleucine. The deprivation of these essential amino acids results in the rapid cessation of plant cell division and growth. Sulfonylureas are remarkable for their high specific activity, whereby application rates in the field are generally over 100 times lower than those for older conventional herbicides. Since sulfonylureas are effective herbicides at low application rates and have very low acute and chronic toxicities to mammalian and other animal species, there has been a rapid rise in the use of this class of herbicide worldwide.

The widespread use of sulfonylurea herbicides has resulted in extensive literature dealing with their biochemical mode of action, environmental fate, and effects on plants. Reviews of the mode of action, environmental fate, and soil relations of sulfonylureas have been presented by others.[1–4] The increasing use of sulfonylureas also has led to concerns about off-target movement to adjacent crops and native plant species. Inadvertent

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exposure to herbicides can occur via soil residues, spray drift, surface water run-off and/or as a result of incomplete or improper cleaning of application equipment. Numerous biological, cultural and environmental factors have been reported to influence the sensitivity of target crops to sulfonylureas. There exists a need to develop a conceptual framework for their interpretation in understanding and assessing the impact of these factors on non-target plants.

Methodology varies for assessing the extent of possible damage to both target and non-target species from sulfonylureas, and it is important to review existing procedures and techniques to understand their limitations and ensure that the use of the data is not over-extended. Assessment of reduced productivity of crops, native plant and forest species as a result of herbicide exposure has been the subject of research for over 40 years, but only recently have methods used to study the area been examined.[5] Tingey *et al.*[6] have reviewed plant-response assessment techniques for air pollutants. They recommend that the term 'damage' be used to describe plant responses that lower product value or impair usefulness, creating an economic loss. Furthermore, the term 'injury' is used to describe other plant responses that are not necessarily related to value loss. The distinction between the use of these terms in helpful when assessment techniques are evaluated, because certain measures such as yield and quality can be directly used to determine damage. These quantitative assessments more directly express productivity and are considered to be more useful in risk analysis than those such as visible injury that may not correlate with production.[7]

The response of native plant and forest species to herbicides is more difficult to quantify than for crop species, since these species are often present in a community with several different species and not in monoculture. While damage to native plants cannot always be expressed in economic terms, their value can be diminished by inadvertent exposure to herbicides affecting their use in many ways such as: (1) altering species composition; (2) lessening the value as a wildlife habitat, recreational area, or aesthetic vista; (3) reducing timber or wood pulp production; (4) impacting lifestock-carrying capacity; and (5) creating undesirable effects on the environment such as soil erosion, emergence of noxious plant species and formation of vegetative barriers.

This review will provide an overview of research quantifying plant-growth effects resulting in crop or plant productivity losses as a result of exposure to sulfonylurea herbicides. The economic significance of crop-loss assessments is discussed, as are evaluation techniques and the ecological importance of effects on native species. This information can be used to improve existing techniques for assessing plant damage and to provide an aid for interpretation of past and future studies.

2 PLANT RESPONSE ASSESSMENT TECHNIQUES

2.1 Visual assessments

Visual assessments for plant injury have frequently been used to determine the effects of exposure to herbicides. Visual symptomology of plants exposed to sulfonylurea herbicides is dependent on plant species, dose and environmental conditions but can include chlorosis, enhanced anthocyanin formation, loss of leaf nyctinasty, abscission, vein discoloration, terminal bud death and necrosis.[8] The type and extent of visual symptoms will vary depending upon the specific sulfonylurea and plant species exposed. There is conflicting information in the literature as to how well visual assessments correlate with end-point assessments of yield or plant productivity. Wall[9] reported a strong linear relationship between visual injury two weeks after sulfonylurea exposure and subsequent crop yield for canola, peas, lentils, sunflower and buckwheat treated with foliar applications of a 2 : 1 combination of thifensulfuron and tribenuron. However, in general, there is a relatively poor relationship between observed foliar injury and yield reduction following applications of sulfonylureas.[10–13] Derksen[14] noted that, when visual ratings were used to measure tolerance of sunflower, mustard or lentil to foliar-applied chlorsulfuron, rates of application could be differentiated but were not a good estimate of the extent of yield loss. Gealy *et al.*[15] found that visual symptoms from thifensulfuron : tribenuron exposure were more pronounced in pea than in lentil and were detectable at levels substantially lower than those that affected final seed yields.

Soil residues of chlorimuron have been shown to cause visual symptoms in cotton, winter wheat, corn and grain sorghum, but yields were unaffected.[16] Similar results were obtained for other crops and native plant species where sulfonylurea herbicide exposures have caused visual responses, but no yield or plant productivity reductions were measured at the end of the growing season.[17–28] Thus, for most situations requiring an assessment of whether non-target plant yield loss will be realized, visual ratings are of little practical value in predicting the effects from sulfonylurea exposure.

Visual symptoms on plants exposed to sulfonylurea herbicides at rates below those causing yield losses are generally transient, and plants can rapidly recover after symptoms are noted.[11,14] One exception is from a study by Fletcher *et al.*[29] who reported reduced yields with almost no foliar symptoms on Royal Anne sweet cherry from chlorsulfuron applied at full-bloom stage. However Bhatti *et al.*[18] could not duplicate these findings in other work on sweet cherry cultivars and found that statistically significant reductions in yield of Bing and Rainier cultivars were always associated with the

appearance of symptoms on leaves. The authors also questioned the validity of the Fletcher *et al.*[29] work for failing to account for the reproductive potential by counting total flowers before sulfonylurea treatment and for enclosing treated cherry branches in a Tyvek fabric cage for several hours.

Frequently, visual symptoms have been used as diagnostic tools to detect the presence of sulfonylureas where off-target movement or soil carryover is suspected.[30–34] Diagnosis based solely upon visual observations should not be considered conclusive, as symptoms from sulfonylurea exposure can closely resemble those caused by other herbicides, diseases, nutrient imbalances, and environmental stresses.[17,35–37] Al-Khatib *et al.*[38] evaluated the use of indicator species selected for sensitivity to sulfonylureas to detect and track airborne herbicides. In their study, glyphosate caused symptoms on indicator species that were difficult to distinguish from symptoms induced by certain sulfonylureas. The intensity and persistence of symptoms can differ among sulfonylurea herbicides on individual plant species,[17,35,36] further complicating and bringing into question the validity of using indicator species to detect unknown herbicides.

Even if visual symptoms are positively attributed to sulfonylurea herbicide exposure, there is no standard framework for quantifying the observed response and expressing it as an economic or productivity loss. Thus, due to the potential ambiguity of visible symptoms in areas where damage to non-target plants from sulfonylurea herbicide exposure is suspected, an objective field survey should be performed by a multi-disciplinary team of qualified scientists such as pathologists, agronomists, and weed scientists. For some situations there may be a need for input from atmospheric chemists, meteorologists and other specialists, as well as chemical analyses to support observations of symptoms.[35,36,39]

Assessment for visible symptoms on plants is simple to perform but difficult to quantify. This is especially true when untreated plants for comparison are not readily available. A variety of procedures are used to record observations, and all are dependent on subjective observation. However, visual assessment techniques have been used successfully to determine cultivar sensitivity to sulfonylureas, other pesticide and safener interactions, sulfonylurea–soil interactions, and sulfonylurea–environment interactions.[10,40–44] The special effort necessary to improve significantly the accuracy of visual assessment is impractical because of the wide variation in leaf morphology, differences in plant susceptibility under varied environmental conditions, and physiological impact of symptoms.

2.2 Plant-growth assessments

A variety of methods have been used to quantify plant-growth responses to sulfonylurea herbicides in the field, and it is not the purpose of this paper to document all research conducted. However, it is fruitful to provide a discussion summarizing the merits of various plant-growth assessment techniques using field methods by relating these responses to crop yield and plant productivity. Selection of an assessment technique should be based upon the intended cultural purpose or ecological significance of the non-target species. It is important to recognize that growth measurements performed soon after sulfonylurea exposure may indicate a temporary herbicidal effect that may not result in plant damage.[15] Thus it may be important to conduct measurement of certain growth responses over time. This is particularly the case for perennials where there is an annual dependence of growth in successive years. It is also incumbent the use of data from plant-growth response measurements is not over-extended and that the proper perspective be placed on the intensity of the effects when this information is used for hazard assessment.

2.2.1 Plant height

The majority of procedures employed for assessing plant growth response to sulfonylurea herbicide exposure involve a measure of partitioning and increase of biomass among plant tissues and organs. Growth responses in the field are often assessed by measuring plant height. Total plant height measurements are made from the soil level to a distinguishing level on the plant such as the top surface of the most recently emerging upper leaf. Total height measurements are generally better suited to monocot species, although there are dicot species with an upright growth architecture where they may be appropriate.

In several studies plant height has been found to be a more sensitive response parameter to sulfonylurea exposure than yield.[19,45–49] Curran *et al.*[20] found that chlorimuron residues in soil caused significant corn height reductions at the three-leaf stage but not at the pretassel stage, although yield reductions were not observed. Corn stalk diameters did not correlate with height reductions or yield. Chlorsulfuron caused significant height reductions in winter wheat but no yield reductions for applications made at the two-tiller stage.[19] Newsom & Shaw[48] reported that, while soybean height for several cultivars was reduced by soil-applied chlorimuron in high moisture regimes, this did not necessarily translate into yield reductions. In some circumstances sections of plant height have been measured, such as lateral branch growth or internode length, to assess sulfonylurea exposure.[50,51] The number of nodes per plant has not been reported to be affected by sulfonylurea exposure.[48] Al-Khatib *et al.*[17] found that, for a perennial forage species (i.e. alfalfa), plant height measurements following foliar sulfonylurea treatment were useful for assessing regrowth after repeated harvests. For this situation, height correlated well with yields, and these measurements of repeated

harvests for regrowth also showed the alfalfa stands recovered from initial sulfonylurea effects.

Plant height and diameter growth measurements are particularly valuable for assessing the effects of sulfonylurea exposure on trees.[52,53] The use of dendrochronological methods to assess growth loss in forest tree species has been described by Huttunen.[54] Foliar-applied chlorsulfuron (rates $>3\%$ of maximum label rate for small grains) significantly reduced sweet cherry height (i.e. reduced internode elongation) and stem diameter.[55] Cole & Newton[52] noted that the average height and height growth of newly planted conifers were less for post-budbreak applications of sulfometuron than for pre-budbreak applications. Although sulfometuron was shown to be less injurious to conifers with increasing age, significant trends in height reduction were observed for established conifers following increasing rates of sulfometuron and with later applications.[56] The degree of injury noted would not preclude the use of sulfometuron for conifer release and reforestation and some species such as grand fir exhibited no reduction in height growth from sulfometuron treatment.[52]

2.2.2 *Plant biomass*

Assessment for effects of sulfonylurea on plant biomass are commonly performed by measuring above-ground growth of foliage expressed as dry or fresh matter weight. These response measurements are particularly suitable for determining herbage yields of native plant, pasture and forage species. Plant population counts have also been used as a measure of biomass reductions. Early reductions in dry or fresh matter accumulation from sulfonylureas do not always translate into yield reductions.[26,57–62] Therefore, for seed- or fruit-yielding crops, biomass determined by removing and weighting above-ground growth before maturation may not provide a direct estimation of yield or quality. Also, biomass measurements taken at later growth stages are generally less sensitive than those at early stages.[59,63] Sequential biomass determinations are useful for studying physiological processes involving relative growth rates, assimilate partitioning, and for understanding the plant's integration of effects over time on yield and productivity.

For some species, secondary branching is increased following sulfonylurea exposure, which can mask effects on early biomass production.[17,59,63,64] Gealy *et al.*[15] found that foliar applications of thifensulfuron and tribenuron more than tripled and quadrupled branching in pea and lentil, respectively. These responses can be contrasted to significant reductions in tillering of barley and reduced branching of flax measured after chlorsulfuron exposure.[51–65]

In some situations individual portions of plants have been assessed for response to sulfonylureas. Al-Khatib *et al.*[36] reported that grape cane weights were affected by foliar-applied chlorsulfuron or thifensulfuron in newly planted grapevine but not in established grapevine. For species with a prostrate growth habit, length of runners has been measured. Melton *et al.*[26] found that foliar-applied chlorimuron applied to cucumbers at the vegetative and flowering stages could reduce runner length but did not adversely affect yield.

Plant population counts have been used to assess biomass response but are of limited value for studying effects of sublethal doses of sulfonylurea herbicides. Holhouser *et al.*[42] reported that corn stand reductions from an interaction between foliar-applied primisulfuron and soil-applied terbufos did not correlate with yield reductions. Stand count measurements have not correlated with effects on emergence and biomass of plants grown in soils containing sublethal doses of sulfonylurea residues.[66] Bocucounis *et al.*[67] reported a lack of correlation between shoot biomass reductions and plant populations for several crops planted into soil treated with chlorimuron. In a field soil previously treated with chlorsulfuron, Brewster & Appleby.[19] found no stand reduction in sugarbeets, but did note a severe reduction in sugarbeet foliage fresh weight (98%). Seed germination and cotyledon opening are usually uninhibited following sulfonylurea exposure. This is explained by the mode of action of these herbicides, since plant seed protein reserves support emergence but subsequent growth is affected due to a lack of branched chain amino acid production.[68] Davidson *et al.*[69] reported that chlorsulfuron had no effects on seed germination of several range-grass species and attributed this to the protein reserves in grass-seed endosperms.

2.2.3 *Root responses*

Root-growth effects have also been assessed following sulfonylurea exposure. The difficulty in extraction from soil, and the loss of natural physical form restrict the ability of investigators to assess effects on roots in field studies. Since soil type and environment will also affect root growth and influence herbicide availability, assessments for effects on root growth from herbicide exposure have limited value unless they are conducted under a wide range of soils and environmental conditions.[70] Root responses to sulfonylurea exposure have been measured by root dry weight, but root length has generally been a more sensitive and less variable measure. Landi & Catizone[71] found that response of corn cultivars to soli-applied chlorsulfuron in the field correlated best with root length rather than with root dry weight or root dry matter. Foliar applications of sulfometuron reduced loblolly pine root length and number during the first 45 days of the growing season but did not result in reduced first year biomass accumulation.[72] Pederson *et al.*[73] assessed the effects of foliar-applied metsulfuron in field-grown barley and found that total root length was reduced early after application; they proposed that there was compensatory root growth

(following metabolic inactivation of the absorbed herbicide) resulting in no yield reductions. Numbers of seminal and coronal roots per plant at 3 and 5 cm below winter wheat caryopsis were reduced by foliar-applied metsulfuron alone and in combination with chlorsulfuron; however, grain yields were not reduced.[62]

Laboratory and greenhouse bioassays for root growth have been used extensively to detect the presence of sulfonylureas in field soils and to study root response effects.[74–76] A bioassay for detection of chlorsulfuron in soil using lentil root growth (length, number and appearance) was correlated to field-grown lentil root-growth studies and was shown to be an effective tool for predicting whether sensitive crops could be safely planted into soils previously treated with chlorsulfuron.

2.2.4 Leaf-growth responses

Effects of sulfonylureas on field-grown plants have been assessed by using physical measurements to quantify leaf growth.[55] Lemerle *et al.*[65] found that sequential leaf area index (LAI) measurements by destructive and non-destructive (radiometer) techniques were effective for field screening and assessing the effects of chlorsulfuron on tolerant and sensitive cultivars of barley. LAI of five broadleaf crops measured two and four weeks after foliar application of thifensulfuron and tribenuron did not correlate consistently with crop yield reductions.[9] For many species there may be visual injury from sulfonylurea exposure but no reduction in LAI.[77] Rate of leaf length extension (RLE) of the third leaf of wheat was used as a non-destructive measure for assessing sensitivity of cultivars for tolerance to chlorsulfuron, but further work is needed to validate this method as a field procedure for predicting yield.[78] Number of tobacco leaves per plant did not correlate well with yield for plants seeded into soil with chlorsulfuron and triasulfuron residues.[63]

2.2.5 Flowering

There has been extensive work performed to evaluate the effects of sulfonylureas on seed and fruit formation in food and fiber crops because of their economic importance, but research concerning flower development has been limited to numbers of flowers produced and time of floral initiation. There have been studies to determine the effects of sulfonylureas on flowers in ornamental species where appearance is important.[79,80] For some sensitive species, foliar exposure of sulfonylureas can delay blossom formation, which can lead to reductions in blossom count and in delay in crop maturity.[9,15,81,82] Exposure of sensitive plants to sulfonylureas at flowering can also result in a delay in fruit development and maturity.[83] Blossom reduction and blossom delay responses better correlate with yield reductions in determinate species. Indeterminate species can recover from initial sulfonylurea injury and compensate with multiple blossom formation.[15] While the number of seed pods per plant has been reported to be reduced by applications of sulfonylureas to legume species, there may be no subsequent yield reduction as pods per plant often correlates poorly with yield.[48]

2.2.6 Biochemical and nutritional responses

In some field studies, physiological and biochemical changes following sulfonylurea exposure have been measured, but the techniques used were not primarily intended to assess effects but rather to study specifically an effect or mode of action. There are few field studies attempting to relate short-term carbon balance of plants to dry-matter production in the long term as a function of sulfonylurea exposure. This may be partially explained by *in-vitro* studies showing that inhibition of photosynthesis by sulfonylureas is not the primary mode of action.[84] In a field study, Gealy *et al.*[15] found that higher concentrations of foliar-applied thifensulfuron: tribenuron reduced net photosynthesis by 37% (mg carbon dioxide fixed dm^{-2} leaf area h^{-1}) two weeks after application, which they attributed to chlorotic growth of newly emerged leaves.

Chlorophyll measurements are not commonly used for assessment of herbicide effects in the field, which is somewhat surprising, since the loss of leaf chlorophyll is the basis for chlorosis visual injury estimates, a symptom commonly reported following exposure to sulfonylureas and many other herbicides. In air-pollution research, the loss of extractable chlorophyll was found to be proportional to decreased leaf weight and a more sensitive measure of effect than visual injury at high injury levels.[85] Gealy *et al.*[15] quantified chlorosis of pea leaves caused by foliar-applied thifensulfuron: tribenuron combinations by determining total chlorophyll A and B concentrations spectrophotometrically. The results of this work showed that chlorophyll content in newly emerged pea leaves was reduced but in older leaves on the same plant the chlorophyll content was not reduced.

The response of field-grown plants to sulfonylureas as determined by nutritional status has been studied. Nutrient levels in foliage of sulfonylurea-treated barley has been studied by Pederson *et al.*[73] Yield reductions in barley from foliar-applied metsulfuron were correlated with marked reductions in plant molybdenum concentrations in foliage for at least six weeks. The authors also noted temporary reductions in concentrations of phosphorus and zinc for four weeks after application with substantial recovery at six weeks. Osborne *et al.*[86] and Bowran & Blacklow[87] found that chlorsulfuron decreased concentrations of a range of elements in wheat plant shoots during early growth by up to 30%. This effect decreased with increasing plant age. There were no reduced nutrient concentrations in mature

grain nor was grain yield reduced. There is a need to examine the mechanisms by which temporary nutrient reductions associated with sulfonylurea applications occur.

3 YIELD ASSESSMENT FOR MEASURING NON-TARGET PLANT RESPONSES

The concept of using field experimentation as the primary method for assessing crop loss is justified by the relevance of the data obtained and has been the basis for assessing losses due to air pollutants and pathogens.[6,88] Field studies integrate the action of a large array of biotic and biotic factors that affect the response of plants to herbicides. Assessment for yield effects in controlled environments are hindered by the gross developmental, physiological and morphological differences between plants grown in the field and those produced under controlled environments.[89] Controlled environments (i.e. growth room and glasshouse studies) can only approximately mimic field conditions, and generally will not replicate conditions such as rainfall pattern, wind, soil type and structure, moisture status and microclimatological influences. Frequently, controlled environments will have the effect of reducing the dose causing a plant response. It is generally accepted that the differences in plant response to a herbicide in the glasshouse and in the field show that controlled environments represent a worst-case and often unrealistic scenario.[89,90] Brown & Farmer[91] and others have emphasized that differences between glasshouse and field results can be highly variable and thus it is not possible to interpret glasshouse data uniformly and so predict field activity. However, glasshouse results will generally provide an additional ‘safety margin’ when estimating risk to non-target plants in the field. The majority of plant responses measured under controlled conditions are collected using short-term tests and rarely is the plant life-cycle taken to completion (yield). Since crop-yield field studies integrate growth over the entire period of productivity, temporary growth responses to herbicides can be related to final yield and quality measurements.

Field experiments designed to assess plant productivity losses as a function of a reduction in the quantity and/or quality of yield should consider what the use of the information will be. There are a myriad of procedures and techniques that have been used to assess crop loss due to sulfonylureas under field conditions. The lack of standardization of field tests is often due to the differences in the objectives of researchers conducting the tests, which can vary by product, region and use pattern. Freemark & Boutin[92] suggest that standardization of field tests is not feasible because the type of field study to be performed depends on the question(s) to be addressed. They propose that guidelines for testing be provided and include the following: clear articulation of the hypothesis, use of multiple doses to differentiate a dose-response relationship from environmental variability, and selection of appropriate end points (e.g. yield) with *a priori* specification of an adverse effect. Since the majority of yield assessment test methods for sulfonylureas are not well standardized, it is important to consider the environmental, edaphic and cultural factors present when interpreting individual studies. The lack of method standardization also limits quantitative comparisons of results and thus decisions involving risk assessment should include all of the available field data.

Crop-yield measurements can be compared to established standards (factoring in market prices and management inputs) within a specific area and this can provide an index for relating yield reductions to economic loss and risk assessment. There are no standardized guidelines for transfer and interpretation of data from field studies to a form usable for economic assessment. US EPA standards for agricultural crops base criteria for nominal yields on the values of measured yields exhibiting structural and functional attributes typical of crops that are experiencing little or no stress.[93] The threshold value for sub-nominal yield due to inadvertent exposure to herbicides may depend on region and local market considerations. The most basic approach for setting sub-nominal threshold values relies on the use of existing regional criteria such as reference sites, yield target projections, and crop classification. However, presently there is no widely accepted procedure for formulating the sub-nominal threshold values for herbicides, and there is a need for a standardized yield index such as net primary productivity (biomass produced from each unit land area) and production efficiency (yield in relation to fertilizer/energy input) in order to specifically relate field-testing studies to economic return.

Crop losses determined by field testing are generally not specifically designed to address economic loss considerations but rather what is the reduction in attainable crop yields (i.e. yields obtained under optimal growing conditions such as in well-managed experimental plots). This is often different from grower goals of preventing a reduction in economic yield (yield obtained using affordable management practices) which is often lower than attainable crop yield. Thus it is important that field studies be designed with the intention of duplicating local grower practices and minimizing artificial inputs from the imposition of the experimental techniques and procedures. It is also advisable to consult with economists to relate biological findings from field studies to economic loss.

It is not the purpose of this paper to discuss the significance of biological results using economic parameters. However a review of field data can provide a foundation for interpretation of biological data so that

experimental observations can be placed into a framework that will enable risk assessments. A comprehensive review of field studies designed to determine effects of sulfonylureas on non-target crops will assist investigators if surveys for crop loss assessment become necessary.

3.1 Yield responses of non-target fruit, grain and fiber crops to sulfonylureas

Non-target crop-yield responses from unpublished and published field studies designed to examine the effects of sulfonylurea herbicides are shown in Table 1. Crops reported in this table are grown for seed, fruit or fiber yields. The advantages of field studies are that they allow investigators to ascertain directly whether yield effects are associated with sulfonylurea exposure and, with well-designed experiments, the precision and accuracy of crop-yield response functions can be quantified. The dose–responses obtained from these studies incorporate a large range of variables including climatic, edaphic, cultural and experimental factors. These features make comparisons between studies difficult, but, where sufficient data exist, it should enable the development of representative exposure–response functions for individual crop species.

The information reported in Table 1 describes the lowest sulfonylurea dose tested in the study which caused a statistically significant yield reduction. It is incumbent upon the individual using the data to determine whether the significance, in the statistical sense, is equated with biological or economic significance. It is also important that the thresholds for crop loss by region and market factors are also considered when these studies are used for risk assessment.

The studies reported in Table 1 are for work where the research was designed to evaluate the effects of sulfonylureas applied directly to foliage, to the soil surrounding an established plant, or where crops were seeded into soil treated with sulfonylureas. There are a number of studies described in the literature where crops are planted into soils treated with a sulfonylurea during the previous cropping period to determine the effects of residual sulfonylureas on non-target crops. While these studies are of value for establishing safe recropping intervals, they are not dealt with in this paper because they do not establish what specific sulfonylurea dose in the soil is creating an effect on a non-target crop yield. Determinations of sulfonylurea concentrations in soil can be related to information such as that provided in Table 1 and may be helpful for assessing the risk of planting a crop into a soil containing a residual sulfonylurea. Ideally, crop response to sulfonylurea residues should be conducted with zero-time herbicide concentration measurements (e.g. analytical, bioassay) obtained in the same fields, to allow for biological and analytical correlations. This permits a more appropriate interpretation, because the biological and analytical data are collected under the same set of edaphic and environmental conditions.

The majority of published work concerning the effects of sulfonylureas on non-target crop yield has been conducted to determine tolerance in the event that there is exposure due to spray drift or contamination of improperly cleaned sprayers. Thifensulfuron alone or thifensulfuron in combination with tribenuron have been most commonly studied because they are frequently used in areas where sensitive crops are also grown. The lowest dose required to cause a statistically significant reduction in yield varies depending upon species, cultivar and study conditions. A generalized finding from these studies is that foliar applications at or shortly before flowering caused greater reductions than at other growth stages.

In many of the field studies, sulfonylureas were compared to other herbicides with different modes of action. When compared to higher use-rate conventional herbicides, the application rates producing an effect in sensitive plants are often lower for sulfonylurea herbicides; however, when expressed as a percentage of the labeled application rate, the sulfonylurea herbicides were often not different from other herbicides.[13,14,18,36] For drift scenarios this is an important consideration, because the response of plants will be dependent upon the volume of spray mixture moving off-target. While the data reported in Table 1 indicate that growers should take measures to avoid spray drift when certain sulfonylureas are applied adjacent to sensitive crops, it is erroneous to relate low herbicide application rates to risk without factoring in the concentration in the spray mixture, the relative potency of the herbicide, and the fraction of total spray mixture moving off-target. For example in a simulated drift study, Al-Khatib *et al.*[36] found that 1/100 of the maximum labeled rate of 2,4-D was more injurious to wine grapes than 1/100 of the rate for thifensulfuron or chlorsulfuron. If the volume of spray mixture moving off-target is not a function of herbicide ingredient, than, as a class, the sulfonylureas should not be expected to be more hazardous than many other herbicides.

Quality (e.g. oil content, fruit size and appearance, fiber length) of the non-target crop as well as quantity parameters were measured in several of the studies. In some circumstances sulfonylureas have reduced both the yield and quality of non-target crops. Reductions in quality generally occurred only with dosages that caused yield reductions. For some crops where yield reductions occurred (i.e. peas, lentils and canola) there was a delay in crop maturity that may not be reflected by any quality parameter measured. This is an important consideration, as delays in crop maturity can increase the risk of frost, insect or disease damage to some crops.

TABLE 1

Summary of Field Studies Evaluating the Effects of Sulfonylureas on yield of Non-target Crops Grown for Fruit, Grain and Fiber

Crop	*Cultivar*	*Year*	*Lowest sulfonylurea dose tested causing significant yield reduction (g AI ha^{-1})*	*Other factors studied*	*Comments*	*Reference*
Blueberry (*Vaccinium angustifolium* Ait.)	Lowbush	1987	Thifensulfuron, no loss at 44 g Chlorimuron, no loss at 70 g	Stem numbers not reduced	Soil-applied to established blueberries	64
			Thifensulfuron, no loss at 22 g Chlorimuron, no loss at 35 g	Chlorimuron increased stem length and buds	Foliar-applied	
Buckwheat (*Fagopyrum esculentum* Moench)	Moench	1992, 1993	Thifensulfuron : tribenuron (2 : 1) loss at 0·23 g	Reduced seed size	Foliar-applied at three-leaf stage	9
Canola (*Brassica napus* L.)	AC Excel	1992, 1993	Thifensulfuron : tribenuron (2 : 1) loss at 0·23 g	Delay in crop maturity, reduced seed size	Foliar-applied at four-leaf stage	9
	Arabella	1994	Thifensulfuron : tribenuron (2 : 1) loss at 0·27 g	Winter canola	Foliar-applied at pre-bolting	97
	AC Excel Legend	1992, 1993	Thifensulfuron, loss at 0·1 g Thifensulfuron : tribenuron (2 : 1) loss at 0·1 g	Seed oil content not affected Seed weight and germination reduced at higher dosages	Foliar-applied at four-leaf stage	98
	Bonneville	1995	Metsulfuron, loss at 0·4 g Thifensulfuron, loss at 0·5 g		Foliar-applied at floral initiation	99
	Hyola 401	1996	Thifensulfuron, loss at 0·53 g Metsulfuron, loss at 0·16 g		Foliar-applied at three- to five-leaf stage	99
	IMC 02	1995	Thifensulfuron : tribenuron (2 : 1) loss at 1·1 g	Spring canola	Foliar-applied at three- to five-leaf stage	100
	IMC-129	1995	Metsulfuron, loss at 0·4 g Thifensulfuron, loss at 0·5 g		Foliar-applied at pre-bud stage	99
	Jackpot	1995	Metsulfuron, loss at 0·16 g Thifensulfuron, loss at 0·5 g		Foliar-applied at bolting	99
	Legend	1995	Thifensulfuron : tribenuron (2 : 1) loss at 0·14 g	Spring canola	Foliar-applied at pre-bud stage	81
	Legend	1995	Thifensulfuron : tribenuron (2 : 1) loss at 0·27 g	Spring canola	Foliar-applied at pre-bud stage	100
	Westar	1995	Metsulfuron, no loss at 0·4 g Thifensulfuron, loss at 2·5 g	Two separate field studies	Foliar-applied at bolting	99
Cantaloupe (*Cucumis melo* L.)		1987	Chlorsulfuron, loss at 8·2 g	No effect on stand	Soil-applied	101
Cherry (*Prunus avium* L.)	Bing Chinook Rainier	1992, 1993	Chlorsulfuron, loss at 0·23 g Chlorsulfuron, loss at 0·03 g Chlorsulfuron, loss at 0·23 g	Most loss at full and post bloom stages No loss at pit hardening stage	Foliar-applied at side green, full and post bloom, and pit hardening stages	18
	Brook	1996	Chlorsulfuron, no loss at 0·4 g Thifensulfuron, no loss at 2·24 g		Foliar-applied at petal fall	102
	Royal Anne	1992, 1993	Chlorsulfuron, loss at 0·125–0·5 g	Most loss at flowering No loss at side green stage	Foliar-applied to individual branches encased in Tyvek	29
	Royal Anne	1995	Chlorsulfuron, loss at 0·4 g Thifensulfuron, loss at 2·24 g	No reduction in sugar content No effects on successive crop	Foliar-applied at late flowering	102
Corn (*Zea mays* L.)	DK 656	1993	Triflusulfuron, loss at 17·5 g		Foliar-applied at second internode	103
	Dekalb 825	1985	Chlorimuron, loss at 9 g	No reduction in stand	Soil preemergence applied	104
	Pioneer 3751	1995	Chlorimuron, no loss at 2·7 g Thifensulfuron, no loss at 2·7 g	Three separate field tests	Foliar-applied at V6, V5, V4–5	105

	Pioneer 3183	1995	Chlorimuron, no loss at 2·7 g Thifensulfuron, no loss at 2·7 g		Foliar-applied at V4–5	105
	Pioneer 3394	1995	Chlorimuron, no loss at 2·7 g Thifensulfuron, no loss at 2·7 g		Foliar-applied at V5–7	105
	Pioneer 3394	1996	Metsulfuron, loss at 2·2 g Chlorimuron, no loss at 2·7 g		Soil-applied and planted same day	105
	Pioneer 3751	1996	Metsulfuron, no loss at 2·2 g Chlorimuron, no loss at 2·7 g		Soil-applied and planted same day	105
Cotton (*Gossypium hirsutum* L.)	Des 422	1986	Chlorsulfuron, no loss at 1·1 g	Flower number, fruit set, and boll size were unaffected	Foliar-applied at pre-flowering stage	45
	DPL 51	1993	Bensulfuron, loss at 2·5 g		Foliar-applied at second leaf stage	106
Cotton	DPL 50 Hartz 1215 PMHS 26	1996	Thifensulfuron, loss at 1·4 g Chlorsulfuron, loss at 0·5 g		Foliar-applied at matchhead square stage	107
Cucumber (*Cucumis sativus* L.)	Dasher II	1995	Chlorimuron, loss at 1·2 g		Foliar-applied at vining	108
	Market More 76	1995	Bensulfuron, no loss at 2·24 g Thifensulfuron, no loss at 2·24 g		Foliar-applied at vining	108
	Market More 76	1995	Bensulfuron, no loss at 2·24 g Thifensulfuron, loss at 2·24 g		Foliar-applied at four- to nine-leaf stage	108
	Poinsett 76	1995	Bensulfuron, no loss at 2·24 g Thifensulfuron, no loss at 2·24 g		Foliar-applied at vining	108
	Speedway	1995	Bensulfuron, loss at 0·8 g Thifensulfuron, no loss at 2·24 g		Foliar-applied at blooming	108
	Sprint 440S	1988	Chlorimuron, loss at 1·2 g	Runner length reduced	Foliar-applied at vegetative, flowering and fruiting stages	26
	Thunder	1995	Bensulfuron, no loss at 2·24 g Thifensulfuron, loss at 2·24 g		Foliar-applied at vining	108
Lentil (*Lens culinaris* Medik.)	Brewer	1991, 1992	Thifensulfuron : tribenuron (2 : 1) <25% loss at 2·3 g		Foliar applications	15
	Chilean	1984	Thifensulfuron loss at 140 g	Plant stands reduced	Soil-applied and planted same day	109
	Chilean	1986	Thifensulfuron, no loss at 140 g Tribenuron, no loss at 140 g	Seed weight was reduced at 140 g of either herbicide	Soil-applied and planted same day	110
	Eston	1992, 1993	Thifensulfuron : tribenuron (2 : 1) loss at 0·23 g	Seed size and germination reduced	Foliar-applied at 10 cm height	9
Mustard (*Brassica juncea* L.) Coss.	Common Brown	1987	Chlorsulfuron, loss at 0·11 g	Combinations with grass herbicides did not enhance loss	Foliar-applied at four- to six-leaf stage	14
Onion (*Allium cepa* L.)	Pukekohe long keeper	1989	Metsulfuron, loss at 0·1 g	Bulb softening and rotting observed	Foliar-applied at early bulbing	83
Pea (*Pisum sativum* L.)	Alaska	1995	Chlorsulfuron, loss at 1·4 g Thifensulfuron, loss at 1·4 g	Delays in crop maturity	Foliar-applied at floral initiation	111
	Alaska	1984	Thifensulfuron no yield loss at 140 g	No effects on plant stand	Soil-applied and planted same day	109
	Alaska	1996	Chlorsulfuron, no loss at 2·5 g Metsulfuron, no loss at 2·5 g	Seed germination	Soil-applied and planted same day	111
	Columbian	1992	Thifensulfuron : tribenuron (2 : 1) loss at 0·23 g	Germination reduced at higher rates	Foliar applications	59
	Columbian	1991, 1992	Thifensulfuron : tribenuron (2 : 1) <25% loss at 2·3 g	Seed size and quality not affected, delayed harvest index	Foliar applications	15

TABLE 1—*Continued*

Crop	*Cultivar*	*Year*	*Lowest sulfonylurea dose tested causing significant yield reduction ($g\ AI\ ha^{-1}$)*	*Other factors studied*	*Comments*	*Reference*
	Columbian	1995	Chlorsulfuron, loss at 0·5 g Thifensulfuron, no loss at 1·4 g	Seed germination	Foliar-applied at floral initiation	111
	Columbian	1996	Chlorsulfuron, loss at 0·5 g Metsulfuron, loss at 0·5 g	Seed germination	Soil-applied and planted same day	111
	Columbian	1996	Chlorsulfuron, loss at 2·5 g Metsulfuron, loss at 2·5 g	Seed germination	Soil-applied and planted same day	111
	Darkskin Perfection	1996	Chlorsulfuron, no loss at 2·5 g Metsulfuron, no loss at 2·5 g	Seed germination	Soil-applied and planted same day	111
	Dual	1995	Chlorsulfuron, loss at 0·5 g Thifensulfuron, loss at 1·4 g	Seed germination	Foliar-applied at floral initiation	111
	Express	1992, 1993	Thifensulfuron : tribenuron (2 : 1) <25% loss at 2·3 g	Germination reduced at higher rates	Foliar-applied at 10 cm	9
	Green Giant	1992	Thifensulfuron : tribenuron (2 : 1) loss at 0·55 g		Foliar applications	59
Pea	Magnus	1995	Chlorsulfuron, loss at 0·5 g Thifensulfuron, loss at 1·4 g	Seed germination	Foliar-applied at floral initiation	111
	Progress	1995	Chlorsulfuron, loss at 0·5 g Thifensulfuron, loss at 1·4 g	Seed germination	Foliar-applied at floral initiation	111
	Puget	1995	Chlorsulfuron, loss at 0·09 Thifensulfuron, loss at 0·5	Seed germination	Foliar-applied at floral initiation	111
Peach (*Prunus persica* (L) Batsch)	Winblo	1995	Bensulfuron, loss at 9·3 g Thifensulfuron, no loss at 112 g	Fruit size	Foliar-applied at 50% petal fall	112
	Artic Glo	1996	Bensulfuron, no loss at 2·2 g Thifensulfuron, loss at 2·2 g	Fruit size	Foliar-applied at 50% petal fall	112
Potato (*Solanum tuberosum* L.)	Katahdin	1984	Chlorimuron, loss at 2·8 g		Foliar-applied at two- to three-leaf	113
	Ilam hardy	1989	Metsulfuron, loss at 1 g	Skin blemishes on tubers	Foliar-applied at preflower	83
	Maris Piper	1991	Thifensulfuron : metsulfuron (10 : 1), loss at 0·45 g	Stored tubers chitted normally, sprout weights reduced at higher rates	Foliar-applied at tuber initiation or bulking	22
	Maris Piper	1992	Metsulfuron, no loss at 0·6 g Thifensulfuron : metsulfuron (10 : 1), loss at 0·45 g	Mean tuber weight reduced but not number of tubers	Foliar-applied at tuber initiation or bulking	114
	Norland	1989, 1990 1991	Tribenuron, loss at 0·3 g	No tuber malformations observed	Foliar-applied three weeks after crop emergence	13
	Russet-Burbank Centennial-Russet	1988	Sulfometuron, loss at 3·8 g Chlorsulfuron, loss at 1·9 g Triasulfuron, loss at 1·9 Metsulfuron, no loss at 0·8 g Thifensulfuron : tribenuron (2 : 1), loss at 7·6 g	Tuber size, cracking, folding, malformation	Foliar application during tuber initiation more damaging to yield and quality than during tuber bulking phase	115
Safflower (*Carthamus tinctorius* L.)		1985	Chlorsulfuron, loss at 18 g Metsulfuron, loss at 18 g Thifensulfuron, no loss at 18 g	No effects on germination	Foliar-applied at 10–15 cm height	116
Sorghum (*Sorghum vulgare* Pers.)		1982	Chlorsulfuron, loss at 9 g		Soil pre-emergence applied	117
	DeKalb	1995	Nicosulfuron, no loss at 0·45 g		Foliar-applied four- to six-leaf	107

	41Y Dekalb 51 NC 7R37E NK 1210 Triumph 46 Pioneer 8500		Thifensulfuron, no loss at 2·24 g			
	Dekalb 51 Dekalb 41YN KS 714 NK 1210	1996	Metsulfuron, no loss at 2·5 g Chlorimuron, no loss at 2·5 g		Soil-applied and planted same day	107
Soybean (*Glycine max* L.)	Hack L2233 Pioneer 9362 Hartz 5545	1995	Rimsulfuron, no loss at 0·5 g Thifensulfuron, no loss at 3 g	Two tests at separate locations with Pioneer 9362 variety	Foliar-applied at V4 stage V3 First trifoliate First trifoliate	103
	Pioneer 9392	1995	Rimsulfuron, loss at 0·27 g Thifensulfuron, no loss at 3 g		Foliar-applied at first trifoliate	103
	Williams '82'	1991, 1992	Nicosulfuron, no loss at 17·4 g Primisulfuron, loss at 4 g	Treatment at R1, V3 growth stages	Foliar applications	10
Sugarbeet (*Beta vulgaris* L.)	HM-WS-91	1993	Thifensulfuron : tribenuron (2 : 1), loss at 12·7 g	Sugar content not reduced	Foliar-applied at four- to six-leaf stage	118
	Mitsuimono hika	1989	Thifensulfuron, loss at 0·6 g	Sugar content not reduced	Foliar-applied at four-leaf stage	119
	Mono-HY 55	1989	Thifensulfuron, loss at 2·7 g	Sugar content not reduced	Foliar-applied at four-leaf stage	120
	VDH 6692	1991	nicosulfuron, loss at 11·2 g	Sugar content reduced	Foliar-applied at eight-leaf stage	103
	WS-88	1993	Rimsulfuron, loss at 35 g		Foliar-applied at four-leaf stage	103
Sugarbeet	HMNSP9	1996	Metsulfuron, loss at 0·5 g Chlorsulfuron, loss at 0·1 g	Sugar content not reduced	Soil-applied and planted same day	121
Sunflower (*Helianthus annuus* L.)	Dahlgren 837	1992, 1993	Thifensulfuron : tribenuron (2 : 1) loss at 0·23 g	Higher doses reduced seed oil content	Foliar-applied at six-leaf growth stage	9
Tomato (*Lycopersicon esculentum* (Mill.)	Scoresby dwarf	1989	Metsulfuron, loss at 0·1 g	Fruit development and maturity delayed	Foliar-applied at flowering	83
	Vis	1987, 1988	Chlorsulfuron, no loss at 10 g	Fruit number increased	Foliar applied at bud formation and early flowering	122
Wine grape (*Vitis vinifera* L.)	Cabernet Sauvignon	1989	Chlorsulfuron, no loss at 135 g Metsulfuron, loss at 72 g	Grape sugar concentrations not affected, no effects in subsequent years	Soil-applied to established grapes	123
	Chardonnay White Reisling	1995	Rimsulfuron, thifensulfuron, no loss at 28 g	Grape sugar concentrations not affected, no effects in subsequent years	Foliar-applied at 50% bloom	124

TABLE 2

Summary of Field Studies Evaluating the Effects of Sulfonylureas on Yield of Crops Grown for Forage and Pasture

Crop	*Cultivar*	*Year*	*Lowest sulfonylurea dose tested causing significant yield reduction* ($g\ AI\ ha^{-1}$)	*Other factors studied*	*Comments*	*Reference*
Alfalfa (*Medicago sativa* L.)	Beaver	1980–1985	Chlorsulfuron, no loss at 30 g	No effects on seed yield of seedling alfalfa No effects on seed yield of established alfalfa for five years from a single application	Foliar-applied at four to seven trifoliate leafed seedlings and established alfalfa at a height of 10–15 cm	24
	Fortress	1993	Triflusulfuron, loss at 18 g Rimsulfuron, loss at 9 g	Forage yield	Foliar-to established alfalfa at 5 in height	103
	Vernal	1990	Chlorsulfuron, thifensulfuron, loss at 0·9 g for first harvest	No effects on subsequent harvests within same cropping year	Foliar-applied at fourth trifoliate leaf stage to established alfalfa	17
Cock's foot (*Dactylis glomerata* L.)	Niva	1995	Chlorsulfuron, no loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Crested dog's tail (*Cynosurus cristatus* L.)		1995	Chlorsulfuron, loss at 7·5 g Tribenuron, loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, loss at 11·2 g	Seed yields also collected	Applied to established pastures four times annually in spring	125
Crested wheatgrass (*Agropyron cristatum* Gaestn.)	Fairway	1985	Chlorsulfuron, no loss at 28 g Metsulfuron, no loss at 6 g Thifensulfuron, no loss at 42 g	No effects on yield of two harvests per year for three years after application	Foliar-applied at two- to three-leaf stage	126
False oat (*Arrhenatherum elatius* Beauv.)		1995	Chlorsulfuron, no loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Golden oat grass (*Trisetum flavescens* Beauv.)		1995	Chlorsulfuron, no loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125

Italian ryegrass (*Lolium multiflorum* Lam.)		1995	Chlorsulfuron, no loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Kleingrass		1988 1989	Chlorsulfuron, no loss at 35 g Metsulfuron, no loss at 35 g Sulfometuron, loss at 35 g	Single harvest	Foliar-applied at three- to four-leaf stage	127
Meadow bromegrass *Bromus commulatus*) Schrad		1985	Chlorsulfuron, no loss at 28 g Metsulfuron, no loss at 6 g Thifensulfuron, no loss at 42 g	No effects on yield of two harvests per year for three years after application	Foliar-applied at two- to three-leaf stage	126
Meadow fescue (*Festuca pratensis* Huds.)		1995	Chlorsulfuron, loss at 7·5 g Tribenuron, loss at 22·5 g Thifensulfuron, loss at 15 g Triasulfuron, loss at 11·2 g	Reduced yield only in mowing immediately after application	Applied to established pastures four times annually in spring	125
Red fescue (*Festuca rubra* L.)		1995	Chlorsulfuron, no loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Ryegrass (*Lolium perenne* L.)		1995	Chlorsulfuron, loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Smooth-stalked meadow grass (*Poa pratensis* L.)		1995	Chlorsulfuron loss at 15 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Seed yield, weight, number	Applied to established pastures four times annually in spring	125
Timothy (*Phleum pratense* L.)	Climax	1985 1986	Chlorsulfuron, no loss at 20 g Metsulfuron, no loss at 4·5 g Thifensulfuron, no loss at 30 g	Yields increased after treatment, two harvests made	Foliar-applied at two-to three-leaf stage	23
	Vetrovsky	1995	Chlorsulfuron, no loss at 7·5 g Tribenuron, no loss at 22·5 g Thifensulfuron, no loss at 15 g Triasulfuron, no loss at 11·2 g	Slight reductions with higher chlorsulfuron rates	Applied to established pastures four times annually in spring	125

TABLE 3
Summary of Studies Evaluating the Effects of Sulfonylureas on Native Plant and Forest Species

Species	*Year*	*Lowest sulfonylurea dose tested causing significant effects ($g\ AI\ ha^{-1}$)*	*Other factors studied*	*Comments*	*Reference*
Abies procera Rehd.	1989	Sulfometuron, loss at 160 g	Suppression of height but not bud growth	Soil- or foliar-applied to three-year-old seedlings	52
Abies grandis Lindl.	1989	Sulfometuron, no loss at 210 g	No suppression of height or bud growth	Soil- or foliar-applied to three-year-old seedlings	52
Acer macrophyllum Pursh.	1986	Metsulfuron, loss at 84 g	Crown volume and stems reduced, with recovery expected	Foliar applied to two-year-old trees	53
Cardamine pratensis L.	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Centaurea nigra L.	1990	Chlorsulfuron : metsulfuron (3 : 1), no loss at 20 g	No suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Digitalis purpurea L.	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Geum urbanum L.	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage and seed yields	Direct-sprayed seedlings	25
Lamiastrum galeobdolon	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Lychnis flow-cuculi L.	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Pinus taeda L.	1990	Sulfometuron, no loss at 30 g	No loss of biomass	Foliar-applied to seedlings	72
Primula vulgaris Huds.	1990	Chlorsulfuron : metsulfuron (3 : 1), no loss at 20 g	No suppression of forage yield, flowering suppressed	Direct-sprayed seedlings	25
Prunella vulgaris (L)	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage and seed yield	Direct-sprayed seedlings	25
Pseudotsuga menziesii Franco	1989	Sulfometuron, loss at 50 g	Suppression of height but not bud growth	Foliar-applied to three-year-old seedlings	52
Silene dioica Clanr.	1990	Chlorsulfuron : metsulfuron (3 : 1), loss at 20 g	Suppression of forage and seed yield	Direct-sprayed seedlings	25
Stachys officinalis Trevir.	1990	Chlorsulfuron : metsulfuron (3 : 1), no loss at 20 g	No suppression of forage yield	Direct-sprayed seedlings	25

3.2 Yield responses of non-target forage and pasture plants to sulfonylureas

A comparison of the yield-response of non-target forage and pasture species from published field studies designed to examine the effects of sulfonylurea herbicides is shown in Table 2. Forage and pasture species yield-responses are most frequently measured by collecting dry matter of above-ground growth. For many species there are several harvests made throughout the course of the growing season. In these situations it is important to determine the effects of herbicides on regrowth after harvest. Studies where repeated harvests occurred offered the advantage of providing information on the long-term effects of herbicides, since the data obtained included the plant's integration of herbicide effects on different component parts and their functioning over time. In all circumstances where repeated harvests were made, there were no long-term effects from sulfonylureas on forage and pasture species that resulted in loss of subsequent harvest yields.

At present there is no qualitative information about the effects of sulfonylureas on forage and pasture plants. Qualitative information such as nutritional value (total soluble carbohydrates, protein content, fiber, stem, foliage ratio) can be related directly to crop quality and may be valuable in interpreting plant responses, particularly where yield reductions have occurred as a result of herbicide exposure.

4 ASSESSMENT OF NATIVE PLANT AND FOREST SPECIES RESPONSES

Yield and growth responses of native plant and forest species from published field studies designed to examine the effects of sulfonylurea herbicides are shown in Table 3. The majority of studies were conducted with single species being tested alone and not in communities. The exception to this is for some of the forest studies, where evaluations were conducted on several species within a forest community.[52,53] The problem of interpreting the effects of herbicides on native plant communities has been examined by Cousens *et al.*[94] The authors make a compelling argument that testing the hypothesis that a herbicide has an effect on a plant community cannot be accomplished by surveys, but only by carefully designed experiments. Furthermore, for most plant community studies, the monitoring programs, experimental designs and analyses serve to generate hypotheses rather than test a hypothesis. Studies designed to evaluate the effects of herbicides on plant communities are complicated by the need to measure the relative abundance of all species present over time along with other factors influencing flora diversity such as animal husbandry, invasion of new species, and environmental effects. Due to these factors, ecological experiments designed to evaluate effects on plant communities are often compromised in their design, and it is imperative that researchers recognize that experimental methods cannot give a quantitative measure of the size of the effect, only a qualitative statement of whether an effect is likely. Cousens *et al.*[94] suggest that the question of how to address hypotheses of herbicide effects on plant communities is still open.

The most comprehensive study conducted to evaluate the effect of sulfonylureas on a range of native plants was performed by Marrs *et al.*[25] In a study to assess the risk that spray drift from application with chlorsulfuron : metsulfuron (3 : 1) would affect adjacent native vegetation, the authors concluded that a buffer zone of only 5–10 m surrounding nature reserves would be required to protect sensitive vegetation from annual sulfonylurea applications. Results of their testing showed that if severe impacts on native plant species occurred (death and severe growth suppression), they were confined to very short distances. This conclusion is in agreement with drift-deposition models collated by Williams *et al.*[95]

The assessment of economic loss caused by herbicides on forest species is also complicated and not without problems.[96] Since there is usually a long production cycle for wood populations, estimated rather than calculated values of woods are used to assess forestry loss, usually by territorial comparison of forest areas from similar sites. Since sulfonylureas are used both for reforestation and herbaceous vegetation management within forests and generally are not highly active on perennial woody species, they would not be expected to pose a significant risk to forest species.

5 CONCLUSION

A review of field studies designed to evaluate the effects of sulfonylurea herbicides on non-target plant responses shows that no single short-term response or assessment technique can be used consistently and reliably to predict non-target crop loss (i.e. yield or quality). There have been numerous quantitative techniques used to measure short-term plant responses to sulfonylurea herbicides in field studies. However, the most frequently used technique to assess short-term plant responses is visual evaluation procedures that are subjective and often ambiguous, especially as related to potential effects on yield and/or quality. No unique visual symptoms have been attributed to sulfonylurea exposure; moreover, symptoms of exposure cannot readily be distinguished from alternative causes such as nutritional imbalances, disease, environmental stresses and other edaphic factors. The presence, type and intensity of visual symptoms resulting from sulfonylurea exposure will differ among specific sulfonylurea herbicides on

individual species. In many studies, visual symptoms observed following sulfonylurea exposure did not correlate with, or result in reductions of, non-target crop yield or quality. However, where reductions in non-target crop yields followed sulfonylurea herbicide exposure, they were always accompanied by obvious visual symptoms.

A review of existing field data for sulfonylureas on non-target plants shows that many sulfonylureas are highly active on certain plants at relatively low dosages. As noted above, the intrinsic sensitivities of non-target plant species to sulfonylurea herbicides are highly compound-specific. These data show that, for most species tested, there was no yield loss at rates below 0·5 g AI ha^{-1}. Such rates generally represent 1/100 or less of the use rates of sulfonylureas. For the most sensitive species, certain sulfonylureas reduced yields at rates of 0·1 g AI ha^{-1}; however this occurred with only a limited number of species in a relatively few studies. Therefore, based upon field studies to date, a rate of about 0·1 g AI ha^{-1} represents the threshold dose required to reduce yields on non-target plants with even the most active sulfonylurea herbicides. While it has been reported that susceptible plants can be effected by sulfonylureas at 1/1000 of the use rate,[5] it is important to note that these findings are based upon short-term plant-response assessments. Such responses have repeatedly been shown not to result in reductions of yield or plant quality.

When sulfonylureas are diluted in spray tanks, it is the herbicide concentration and fraction of spray mixture moving off-target that is of more relevance than the intrinsic toxicity. When compared to other herbicide families, the application rates producing an effect in sensitive plants are often lower for sulfonylureas. However, when expressed as a percentage of the labeled application rate, the sulfonylureas are not different from many other herbicides. When this information is coupled with exposure factors and environmental fate characteristics, the sulfonylurea herbicide family would not be expected to represent a unique hazard to non-target plants.

Like others,[90] we believe there is a need for the use of standardized protocols when field tests are conducted to assess the effects of herbicides on non-target plant species. Hazard assessments for effects on non-target plants have generally been conducted on a case-by-case basis. Where limited field study data are available for certain sulfonylureas on non-target crops, it is important to recognize the need for data from multiple locations before definitive conclusions can be reached. Such studies also need to include economic or ecological impact measurements (e.g. yield, quality) in addition to short-term response data (i.e. visual assessments). It is important to determine what constitutes an economically or ecologically significant effect prior to conducting tests in order to determine which assessment techniques are most appropriate.

In addition to information from well-designed field experiments, it is important to consider data describing environmental fate and patterns of use (e.g., persistence, volatility, concentrations, mobility, methods of application and meteorological conditions) in order to assess properly the likelihood that a hazard exists. In addition, the mechanism of exposure being assessed must be considered in relationship to the duration and route of exposure. Short-term plant responses must be quantified with end-term response measures if risk assessments are to be improved. This information is essential for conducting any sort of quantitative hazard assessment and determining mitigation options for non-target plants.

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